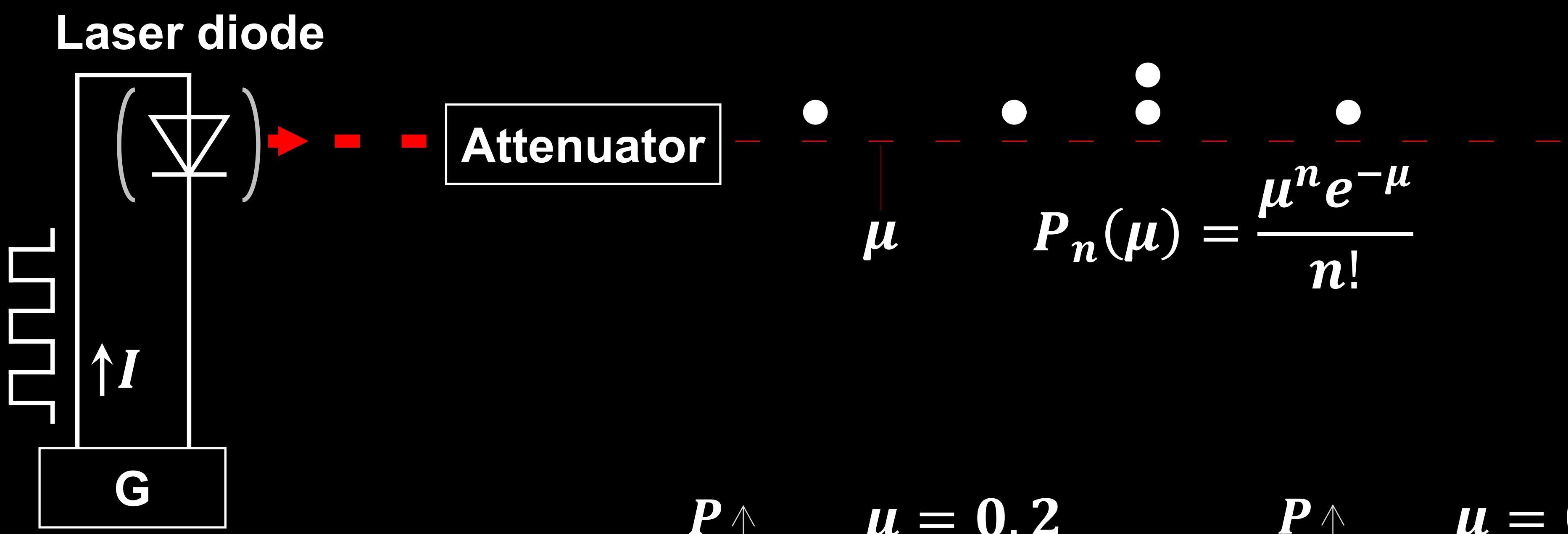
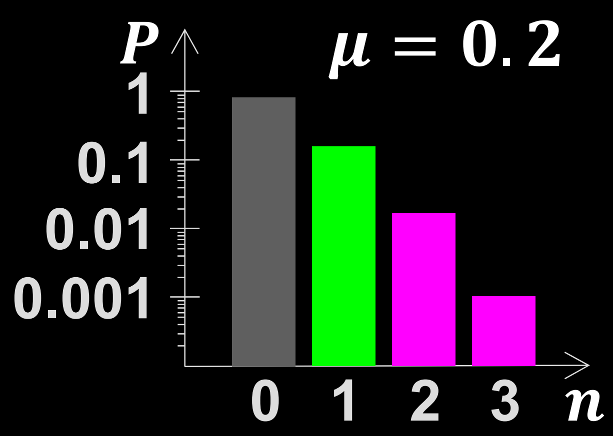
Components of quantum-optical systems

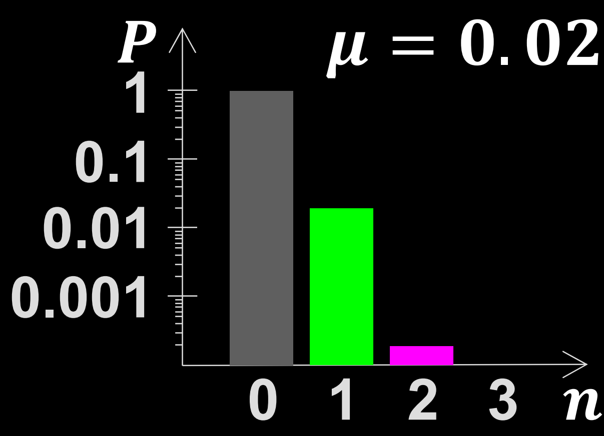
Photon sources ____ **Transmission channels** ____ **“Processing” elements** ____ **Photon detectors**

Attenuated laser source



$$P_n(\mu) = \frac{\mu^n e^{-\mu}}{n!}$$





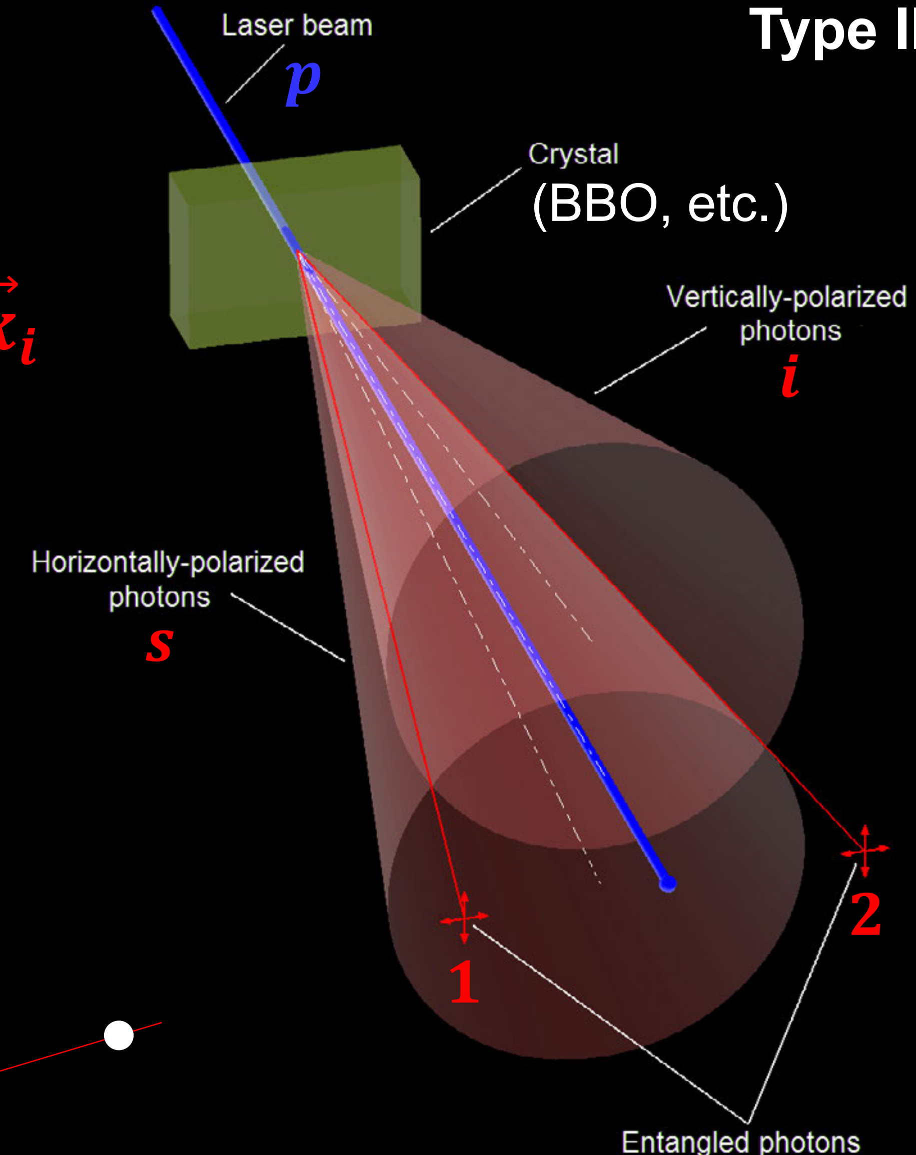
S. J. van Enk, C. A. Fuchs, arXiv:quant-ph/0111157

Spontaneous parametric down-conversion

Type II

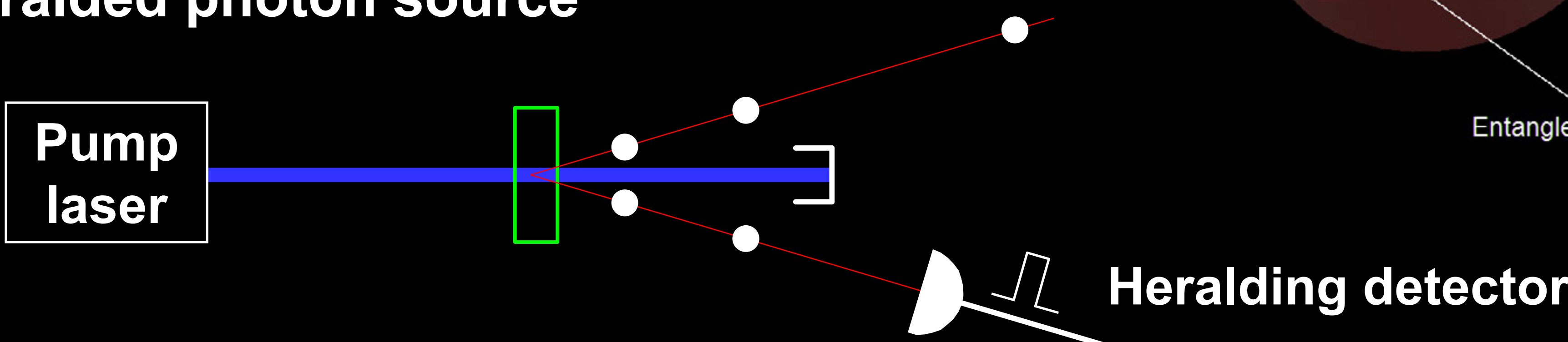
Energy conservation: $\omega_p = \omega_s + \omega_i$

Momentum conservation: $\vec{k}_p = \vec{k}_s + \vec{k}_i$



$$|\psi\rangle = (|H_1, V_2\rangle + |V_1, H_2\rangle)/\sqrt{2}$$

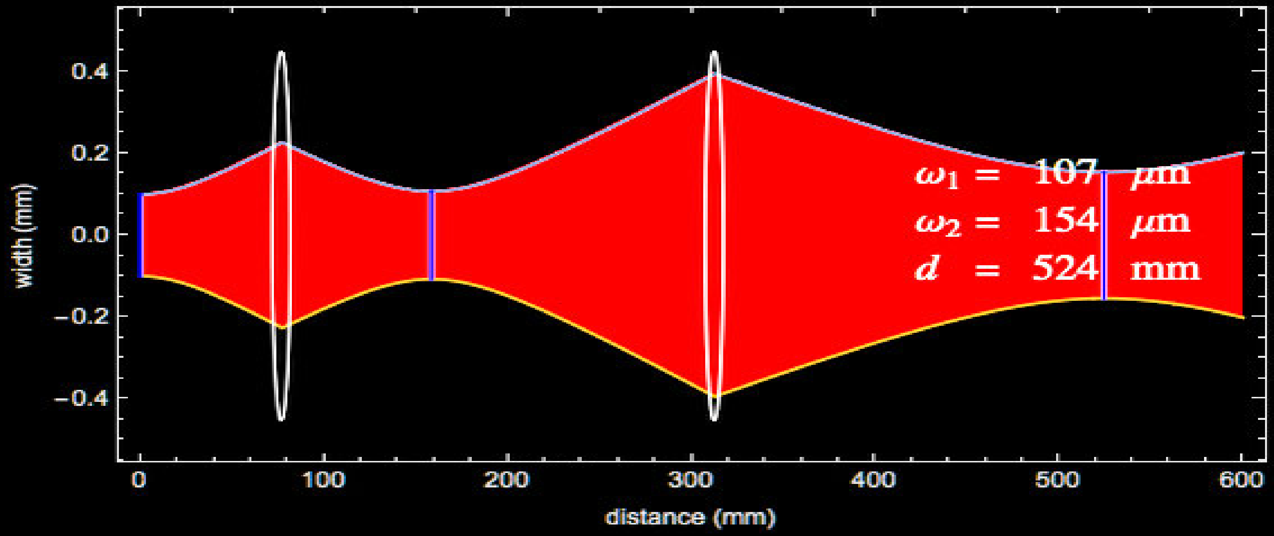
Heralded photon source

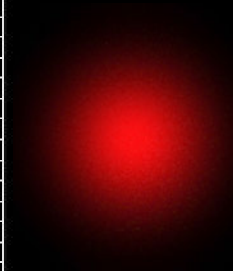


P. G. Kwiat *et al.*, Phys. Rev. Lett. **75**, 4337 (1995)

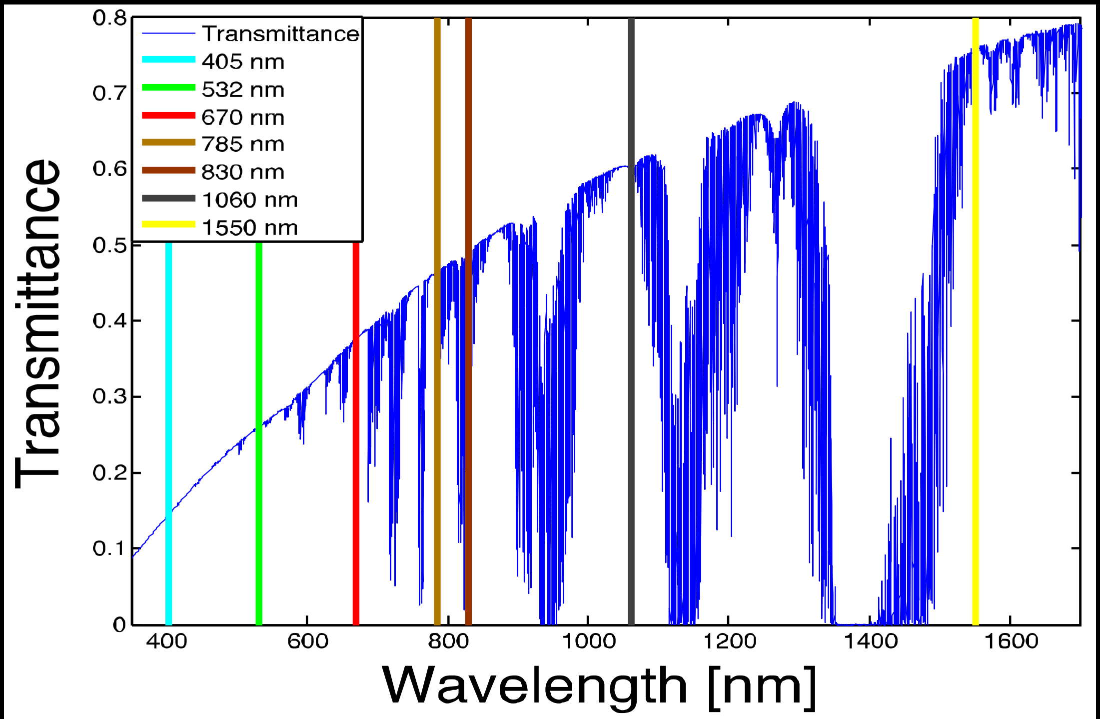
Transmission in free space

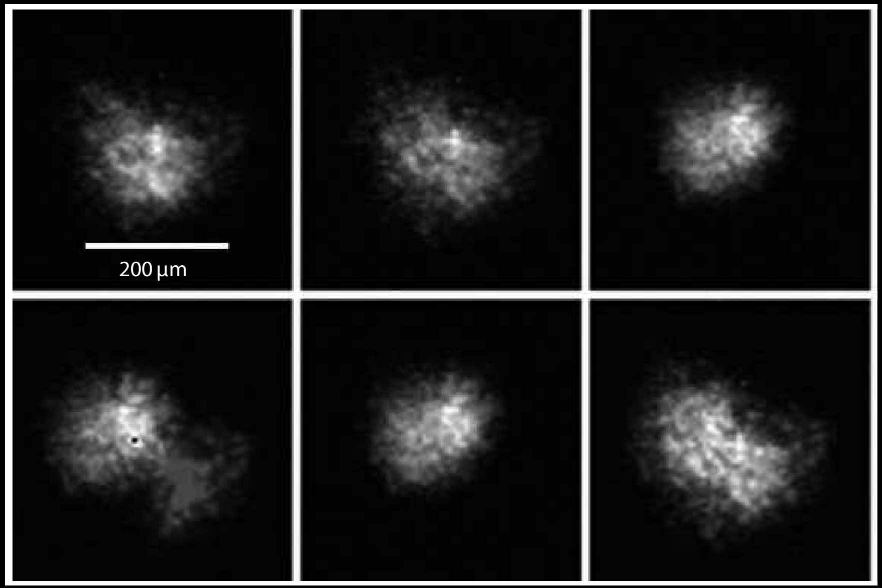
Vacuum:
Gaussian optics





Atmosphere: loss, turbulence





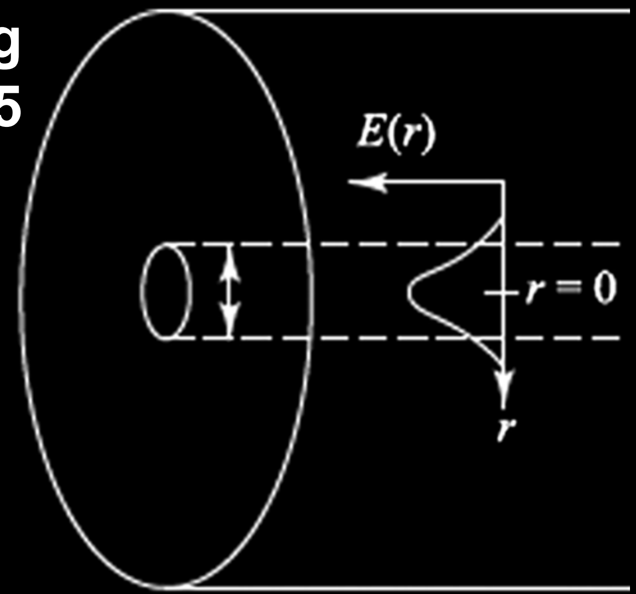
Images reprinted from: https://demonstrations.wolfram.com/GaussianBeamPropagationThroughTwoLenses/; Wikipedia; J.-P. Bourgoin *et al.*, New J. Phys. **15**, 023006 (2013); R. Ursin *et al.*, Nat. Phys. **3**, 481 (2007)

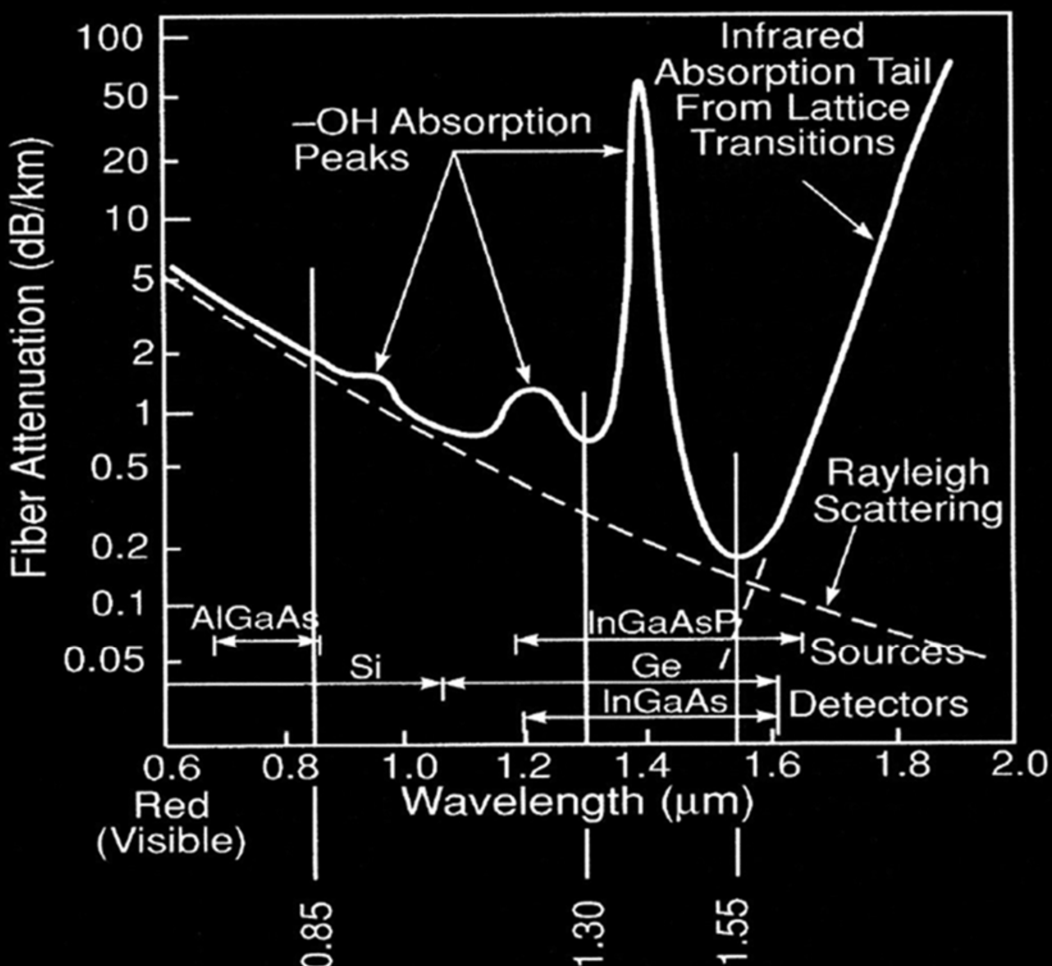
Transmission in optical fiber

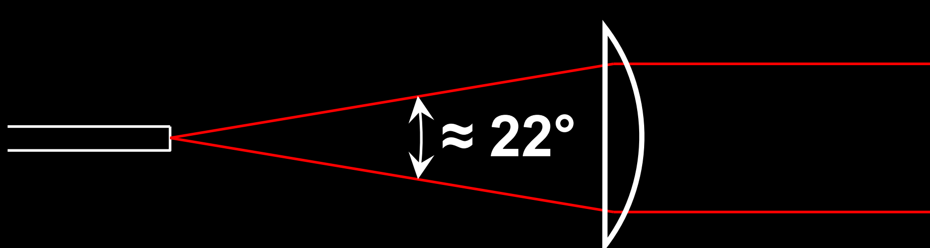
Single-mode fiber

125 µm diameter cladding
fused quartz, n_1 = 1.45

8 µm diameter core
$n_2 > n_1$

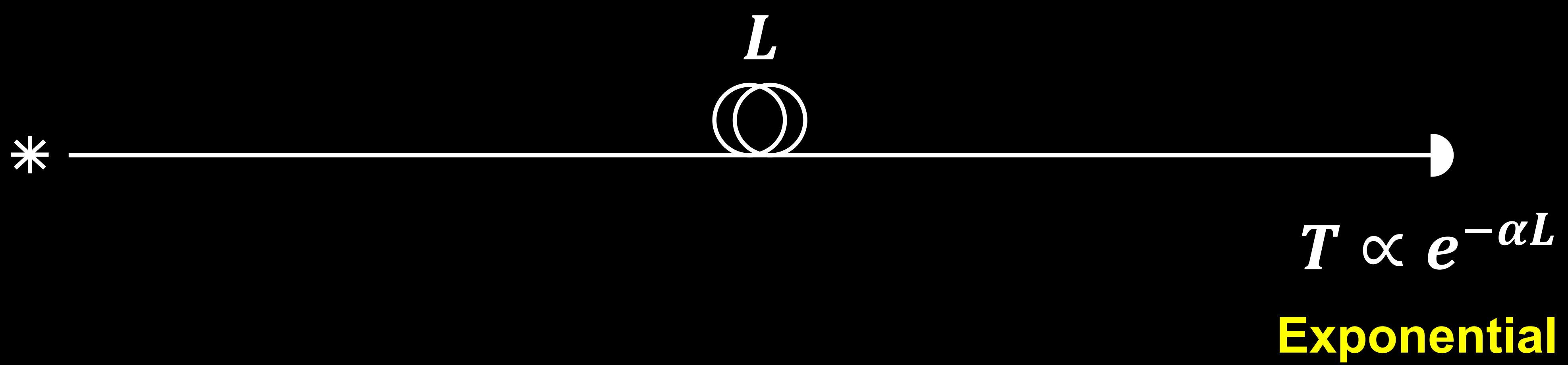


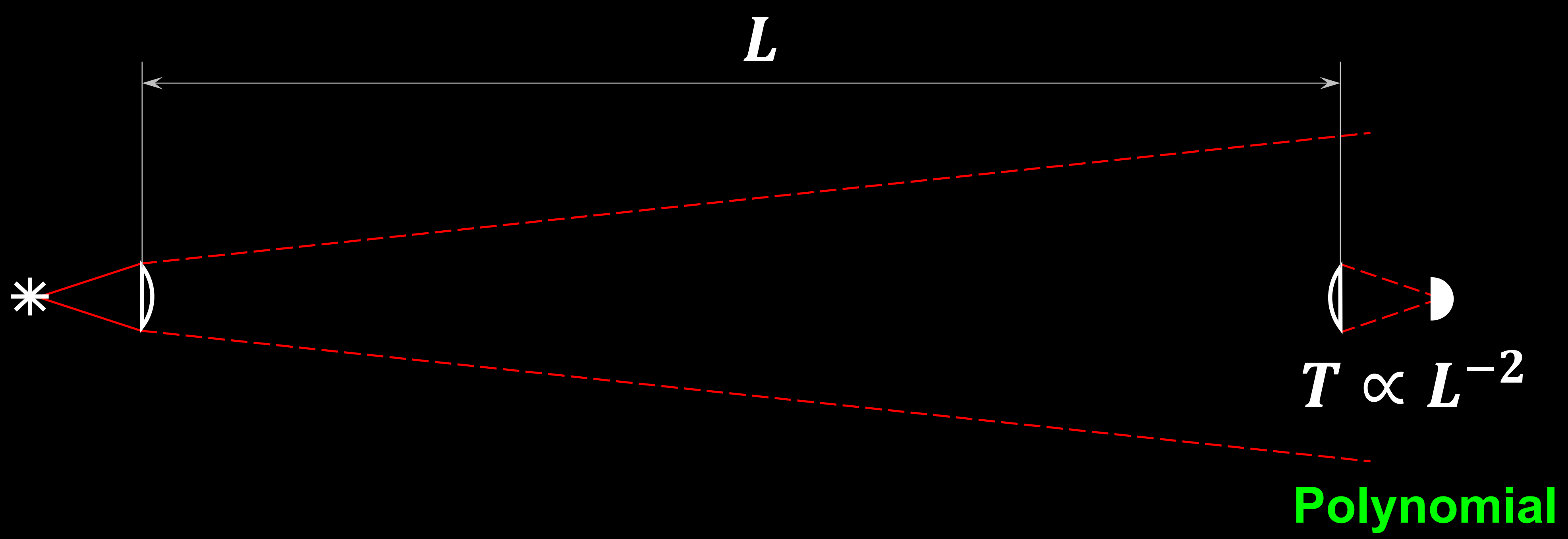




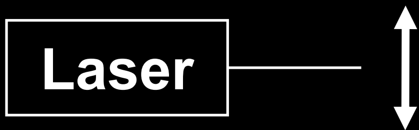
Images reprinted from: G. Keiser *et al.*, J. Biomed. Opt. **19**, 080902 (2014); ViaLite

Fiber vs. beam in vacuum: loss scaling

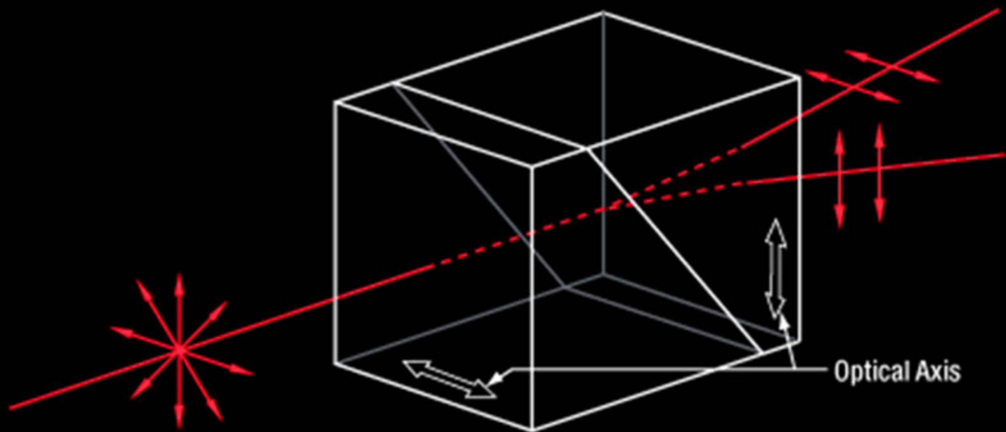




Polarizers

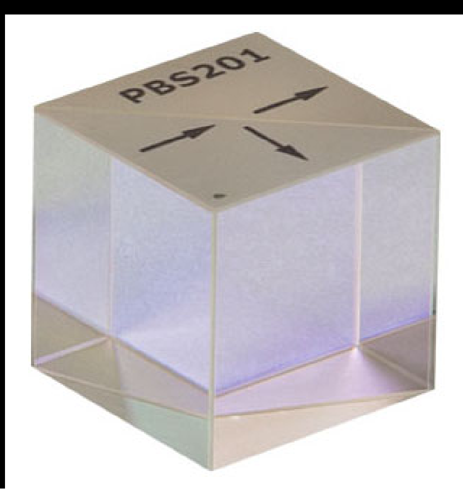


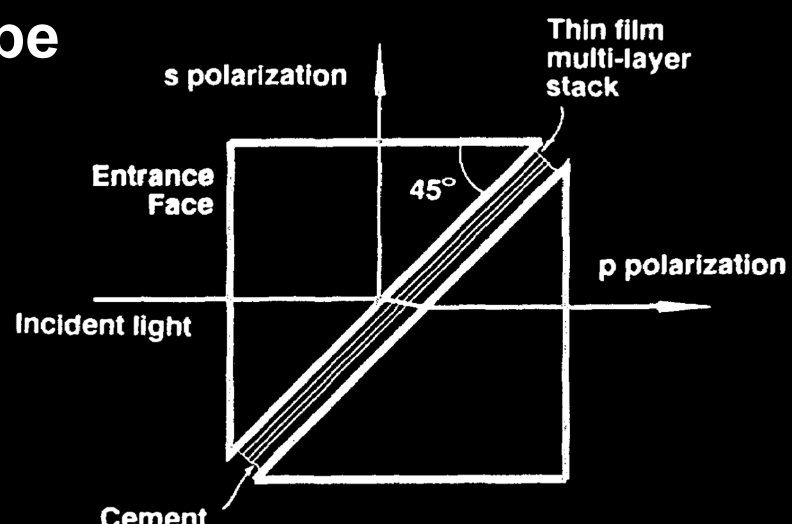
Birefringent polarizing beamsplitter



Wollaston prism

Polarizing beamsplitter cube



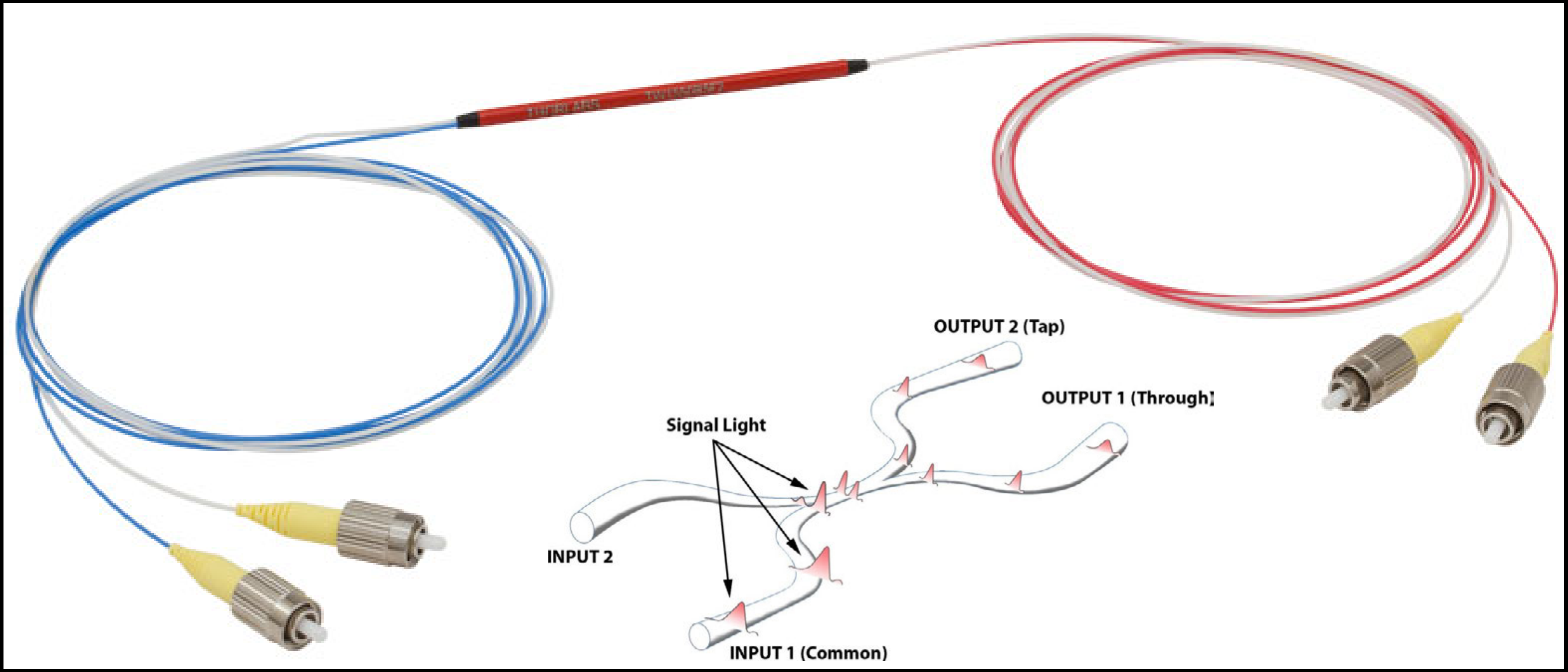


Images reprinted from: Thorlabs; J. L. Pezzaniti, R. A. Chipman, Appl. Opt. **33**, 1916 (1994)

Beamsplitters

50:50
10:90
1:99

Fiber-optic fused beamsplitter (or coupler)

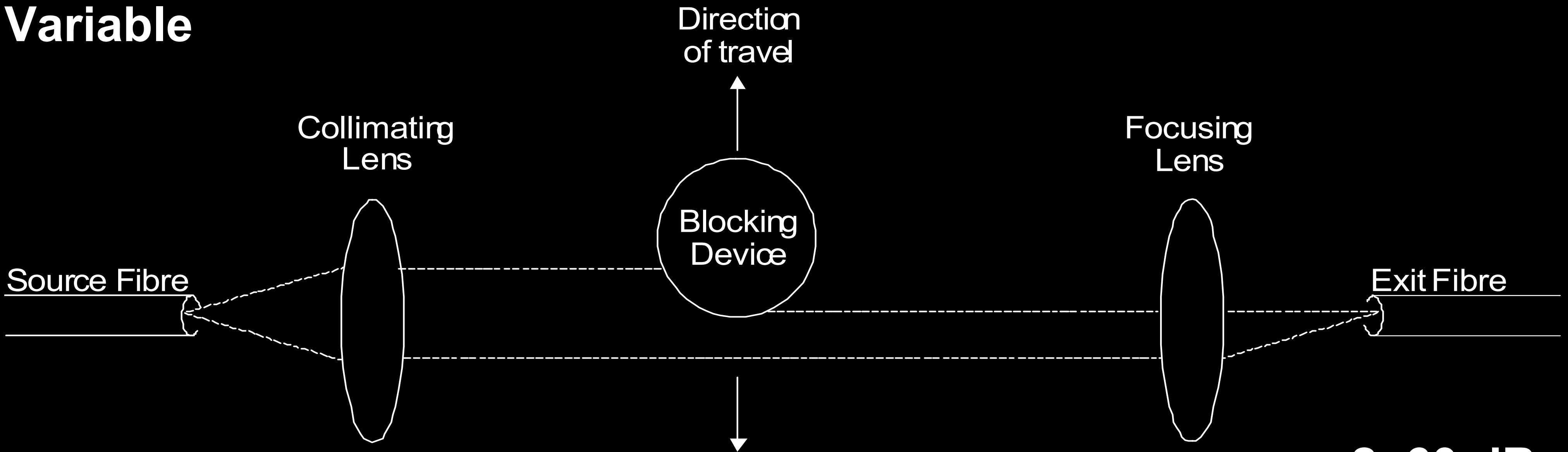


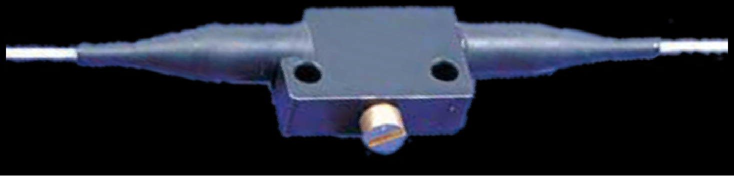
Images reprinted from: Thorlabs; Go!Foton

Attenuators

Absorbing or partially reflecting coated glass

Variable





2–60 dB

Wavelength filters

Colored glass

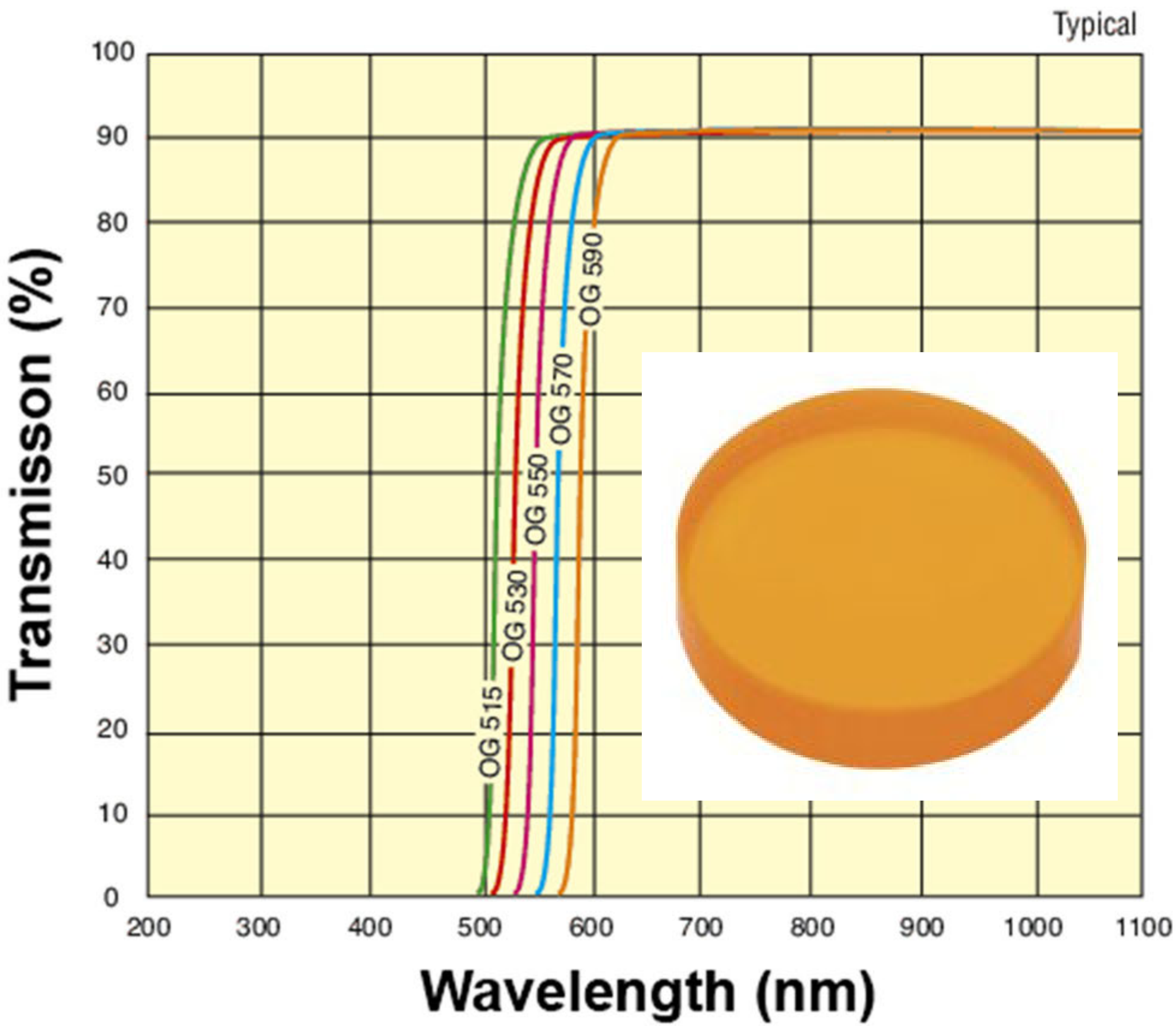
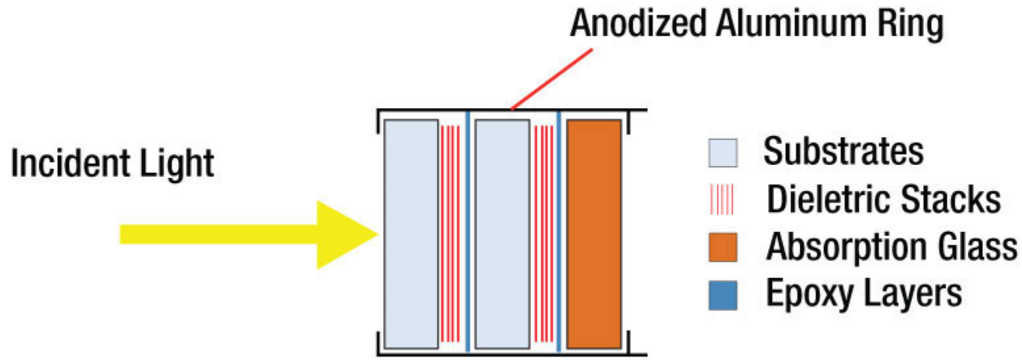
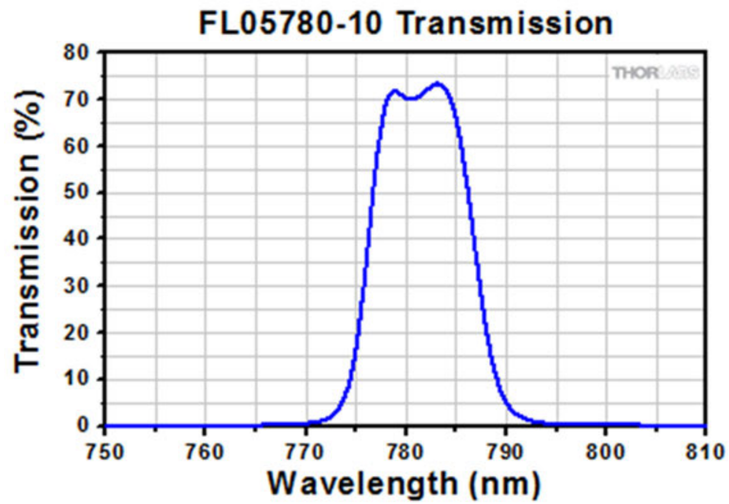


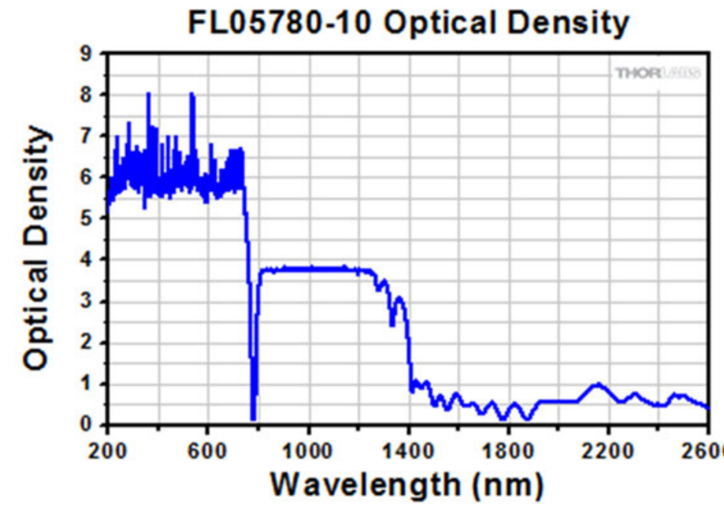
Image reprinted from: Newport

Wavelength filters

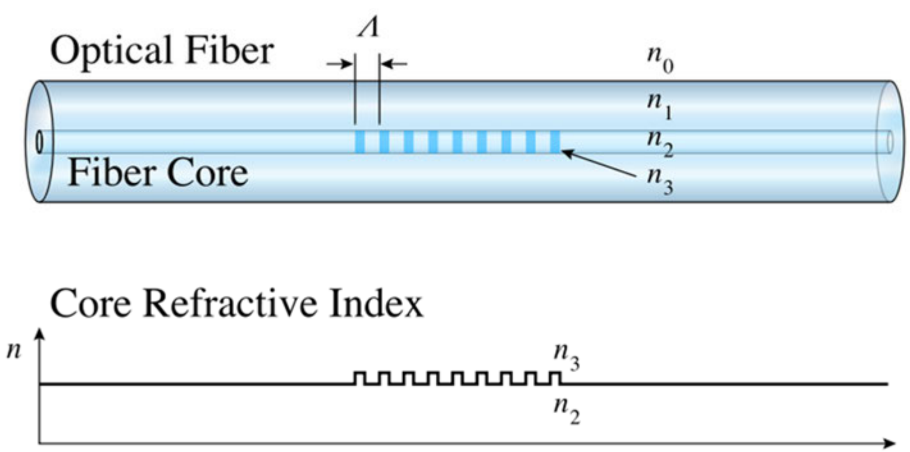
Interference filter

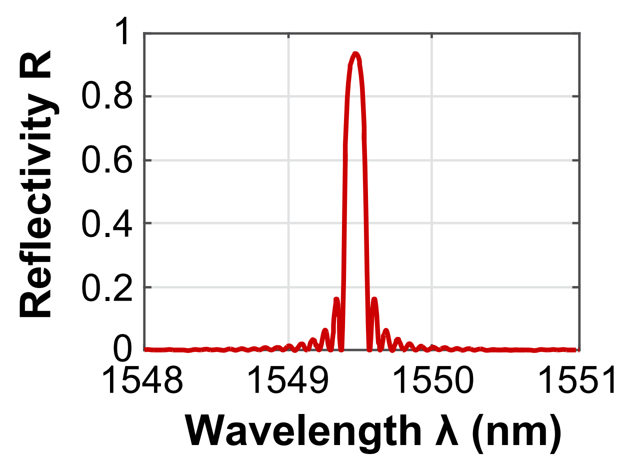






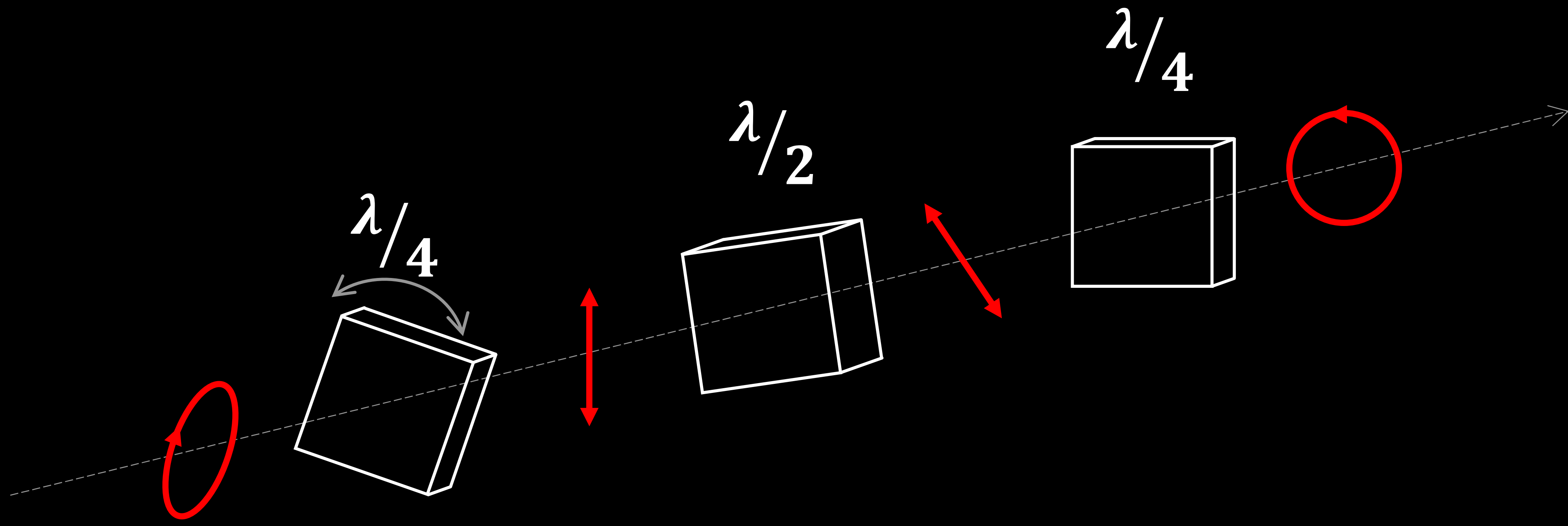
Fiber Bragg grating





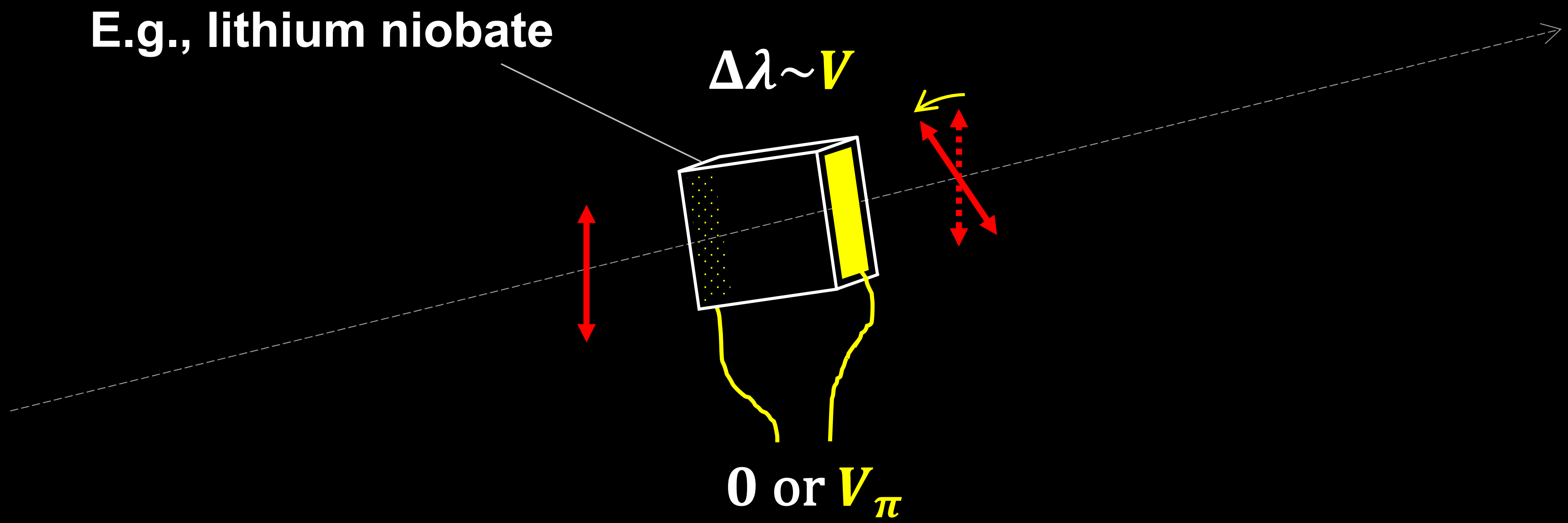
Images reprinted from: Thorlabs; Wikipedia; F. Seng *et al.*, Appl. Opt. **55**, 7179 (2016)

Polarization controller (slow)



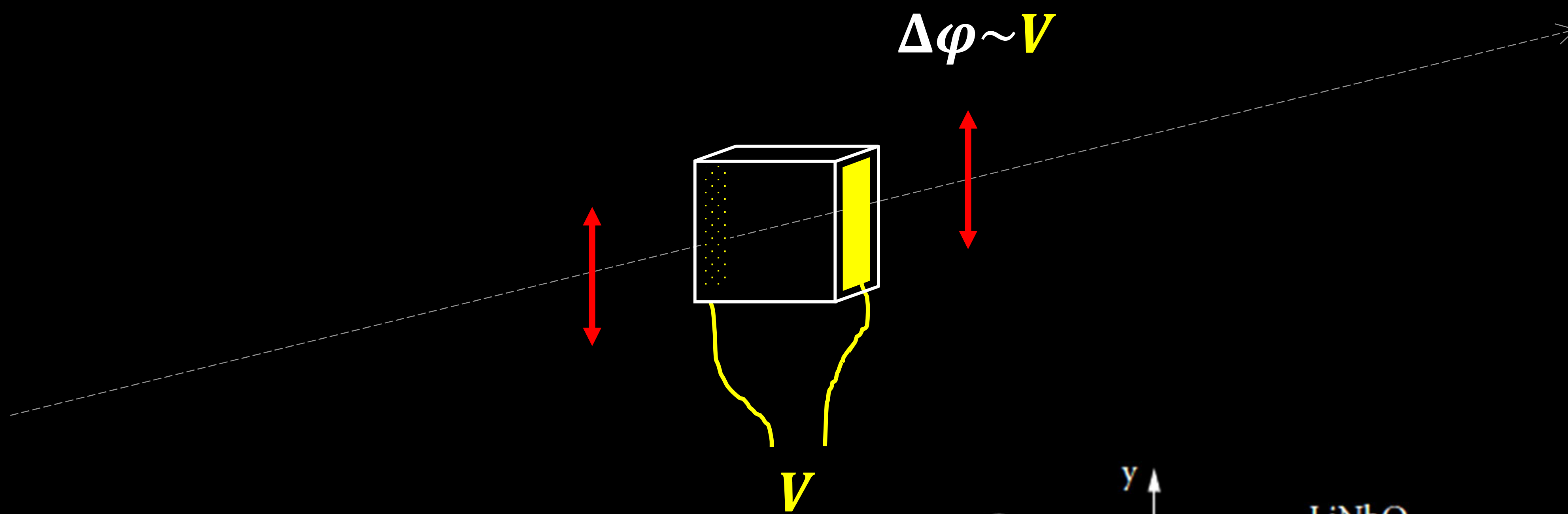
www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=343

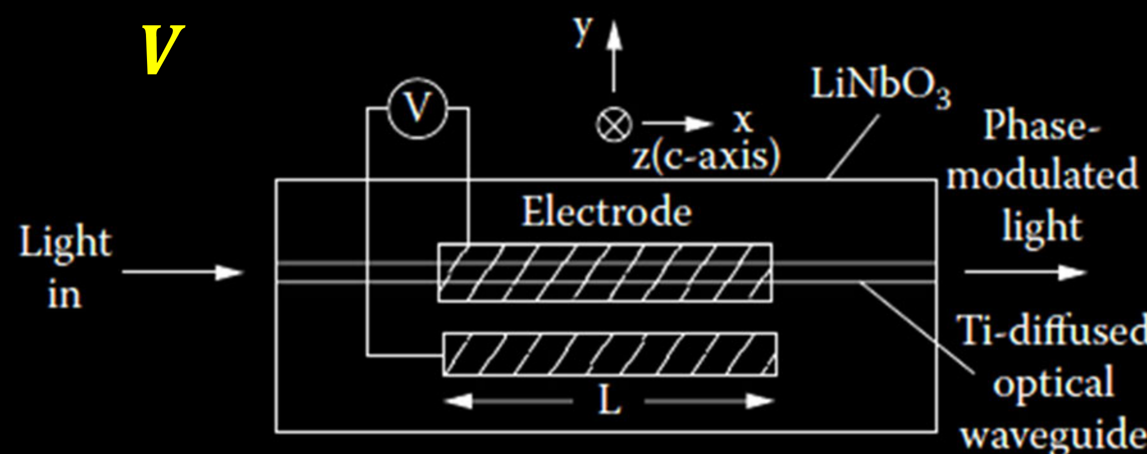
Polarization modulator (fast)

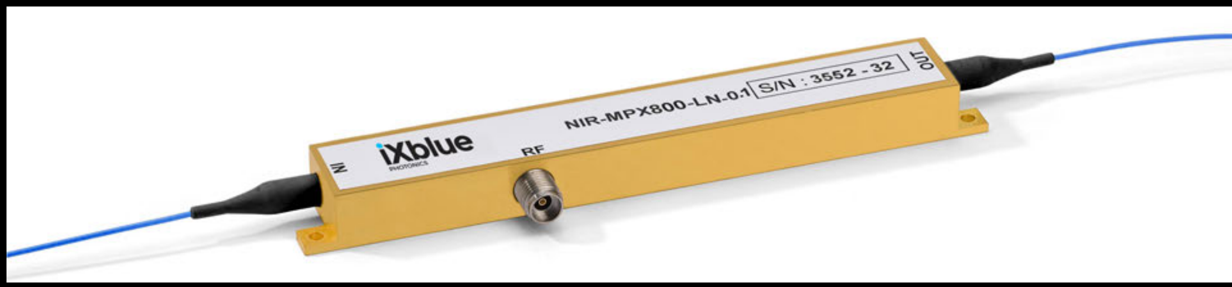


Pockels cell

Phase modulator

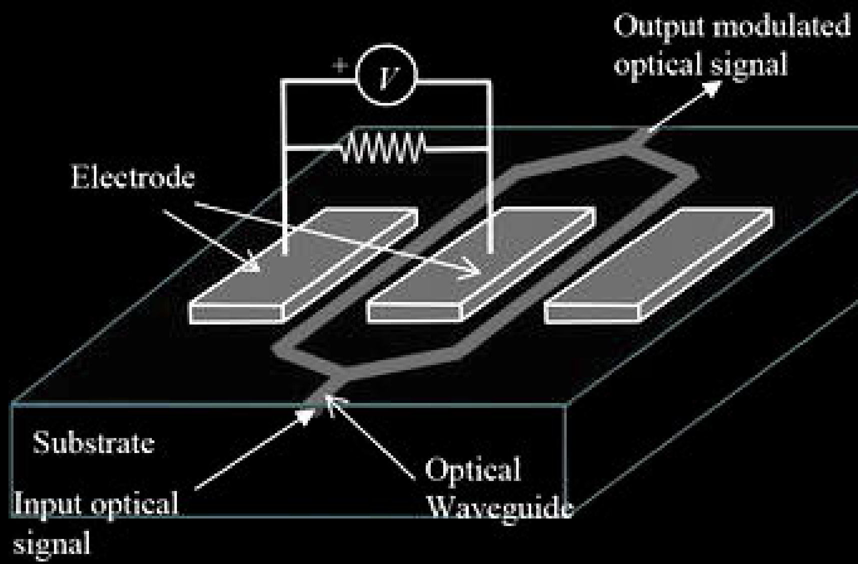


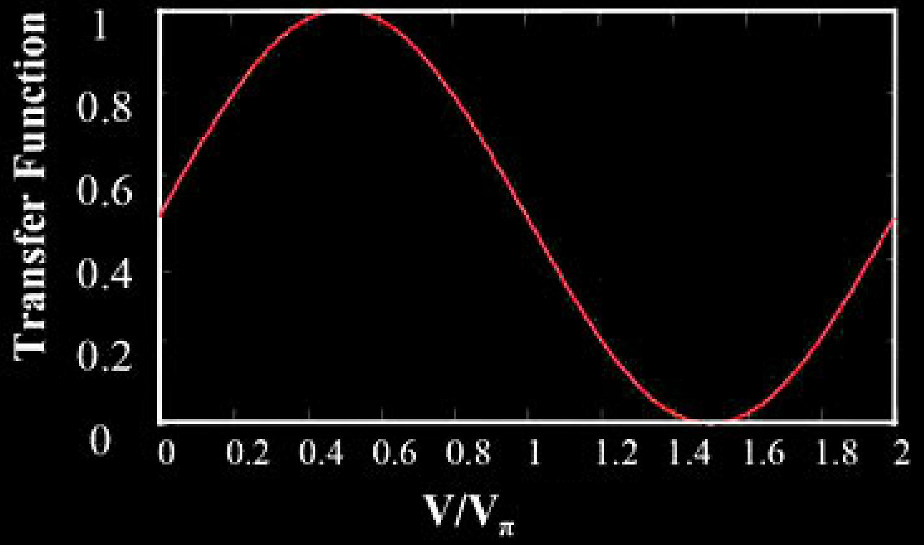




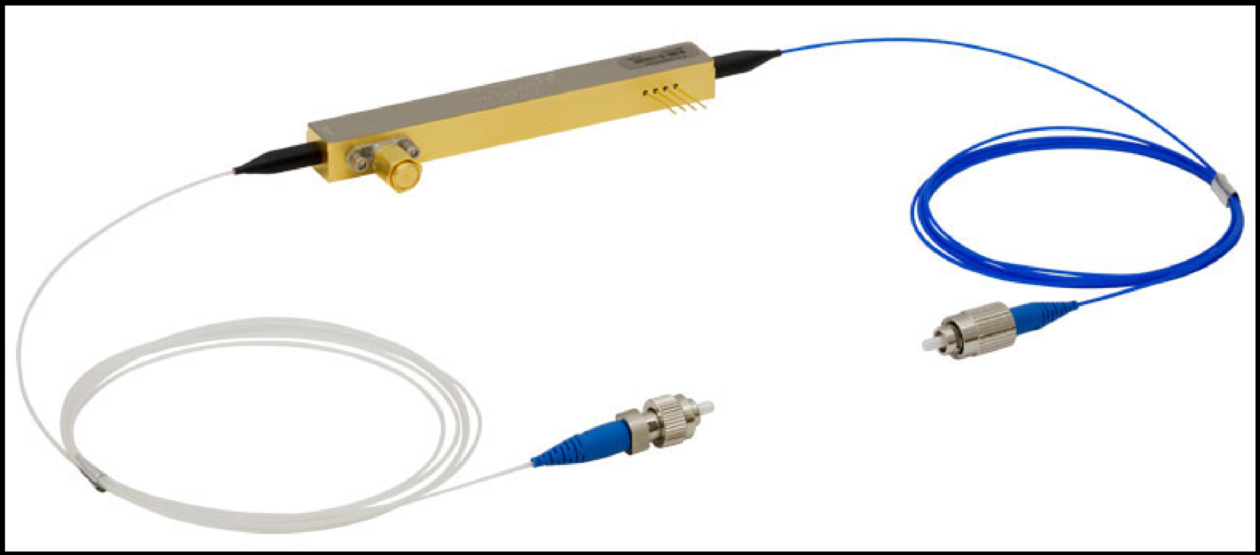
Images reprinted from: A. E.-N. A. Mohamed *et al.*, Int. J. Multidiscip. Sci. Eng. **2**, 13 (2011); iXblue Photonics

Intensity modulator





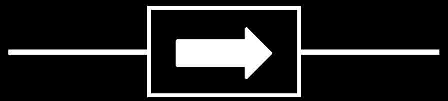
Mach-Zehnder interferometer

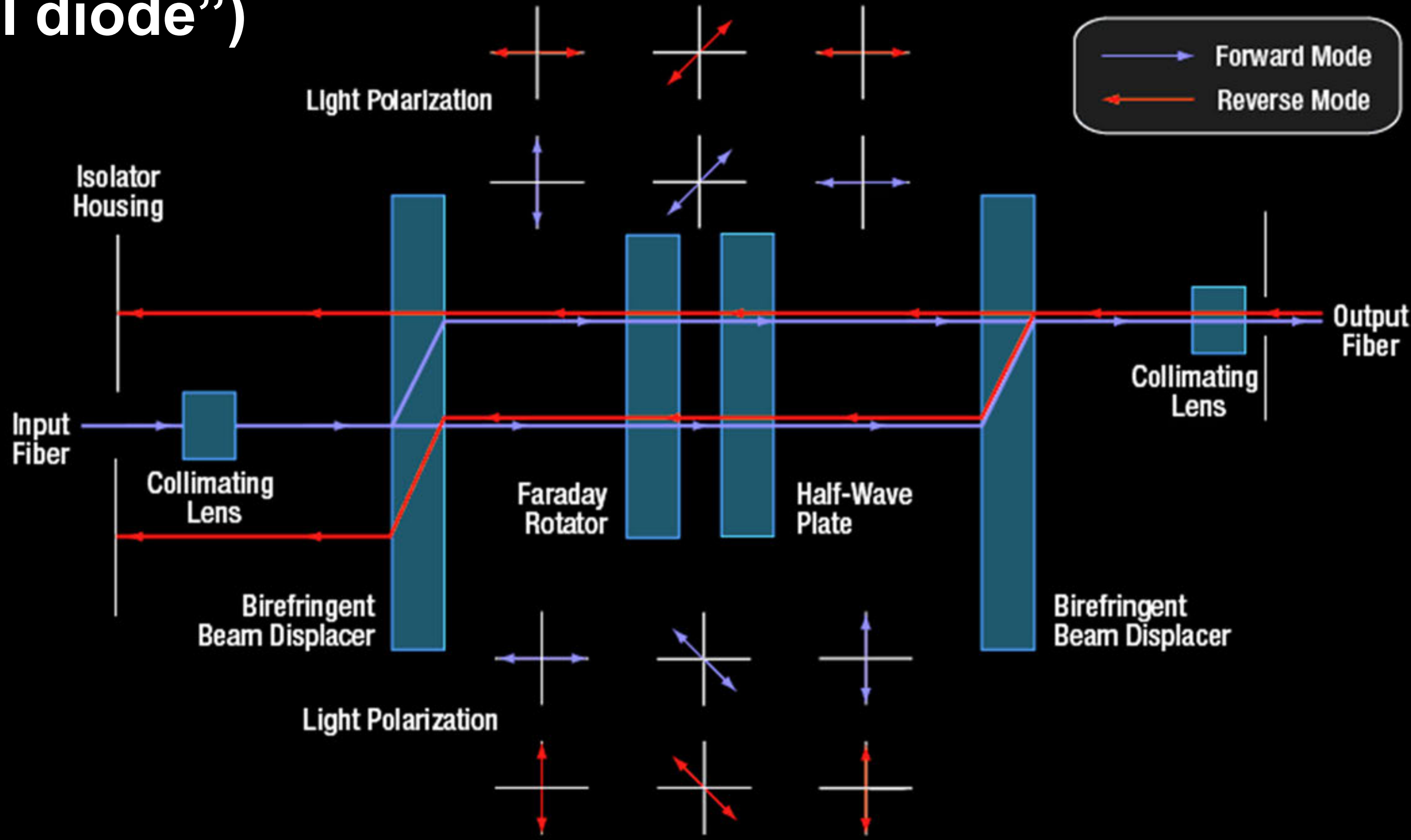


Images reprinted from: Optical Communication Technology, P. Pinho, ed., IntechOpen (2017); Thorlabs

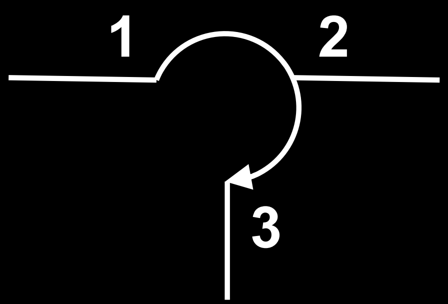
Directional elements

Isolator (an "optical diode")



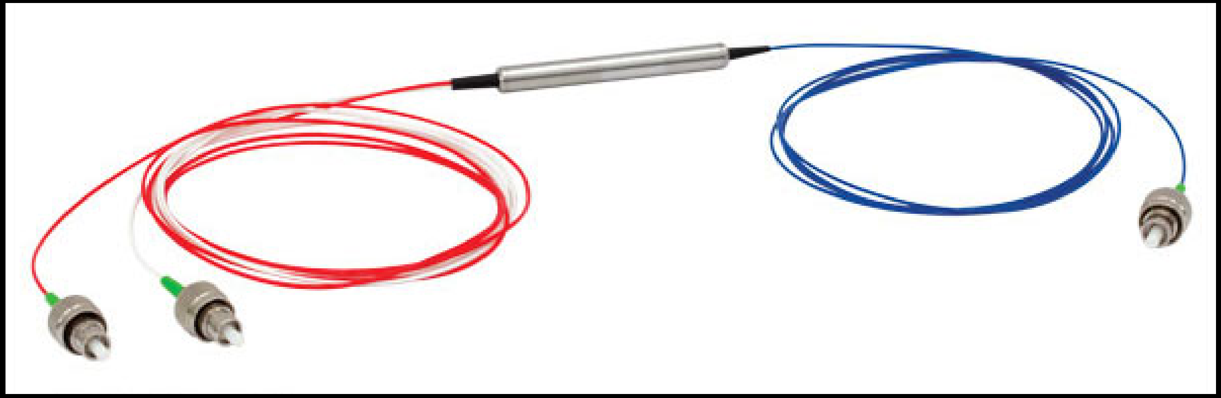


Circulator



$1 \rightarrow 2$

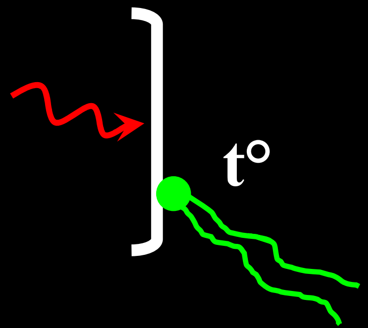
$2 \rightarrow 3$



Optical power meters

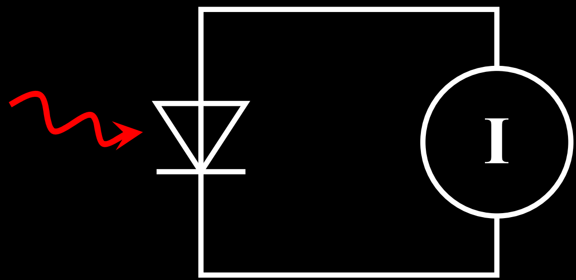
Thermal

> 10 µW



Photodiode

> 0.1 nW



Single-photon detectors

Photon energy

$$E = \frac{hc}{\lambda} = \frac{19.9 \times 10^{-26}}{1.55 \times 10^{-6}} = 1.28 \times 10^{-19}\ \mathrm{J}$$

⬇

Need a gain mechanism

Photomultiplier tube

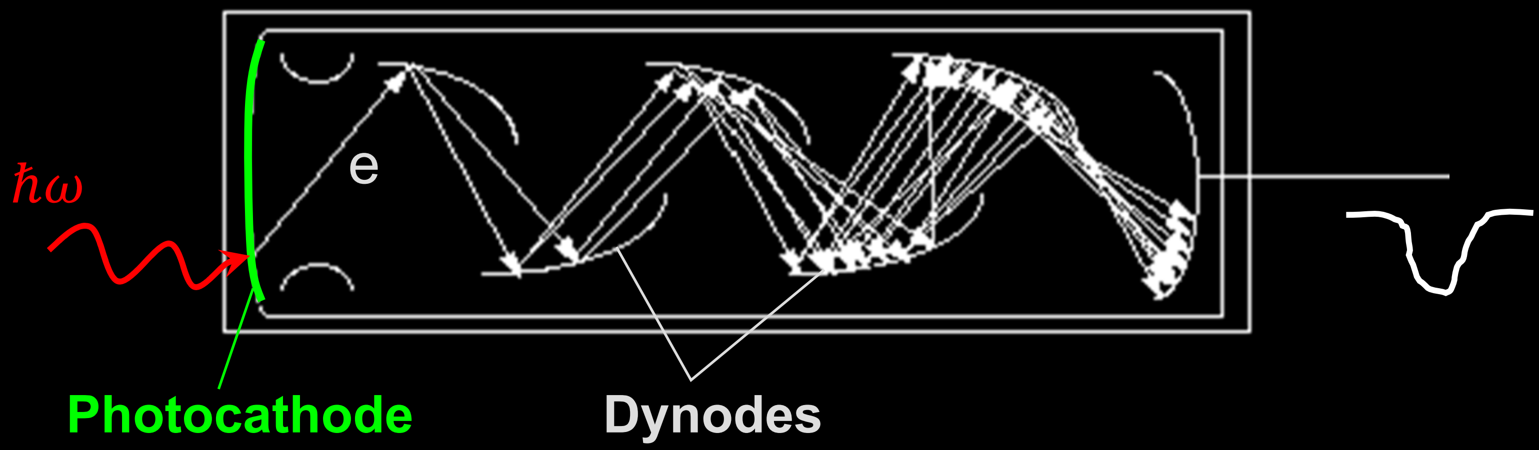
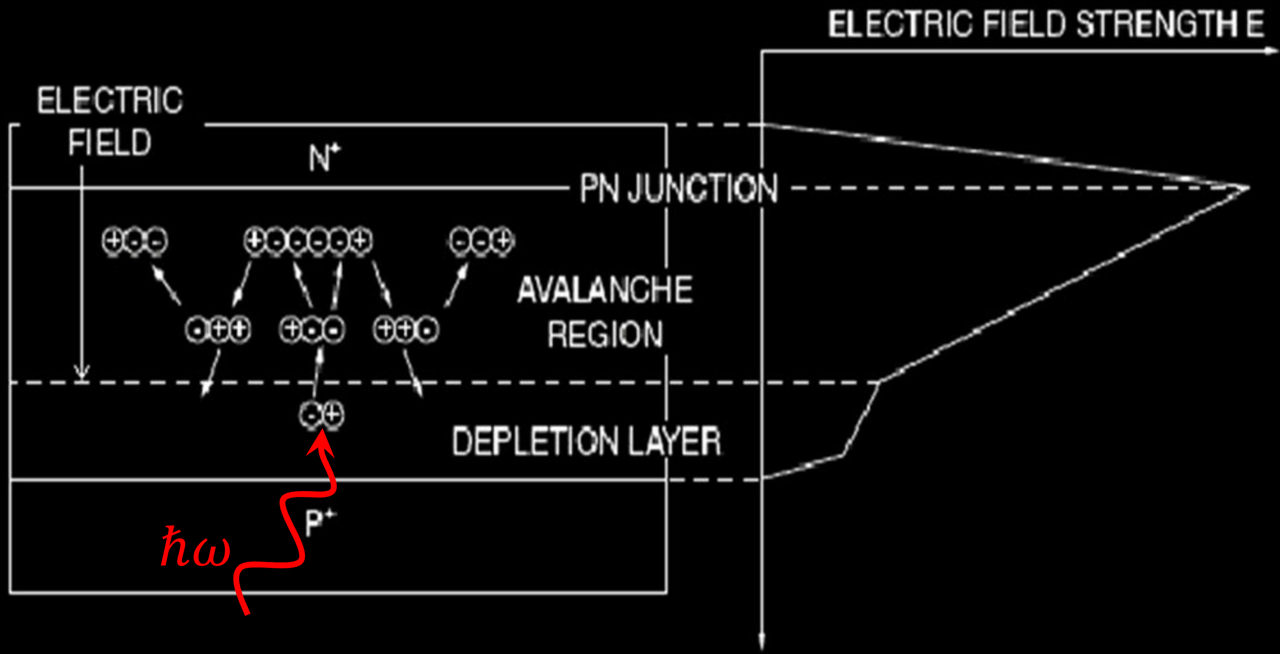
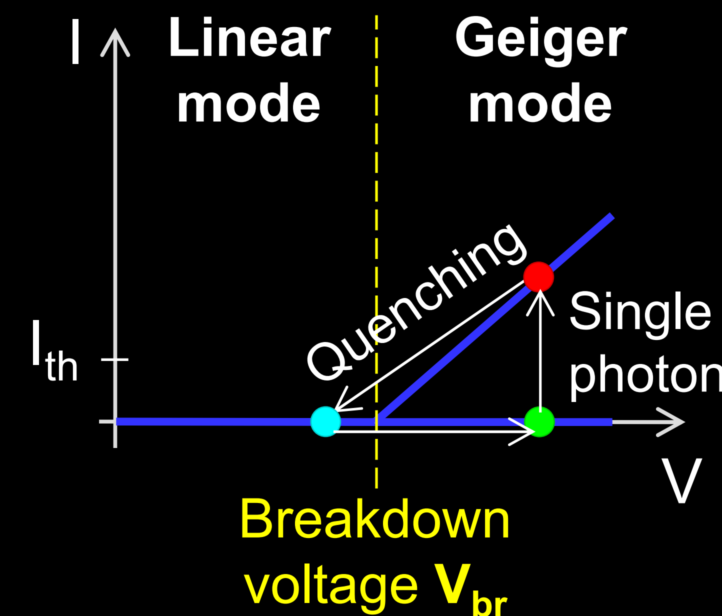
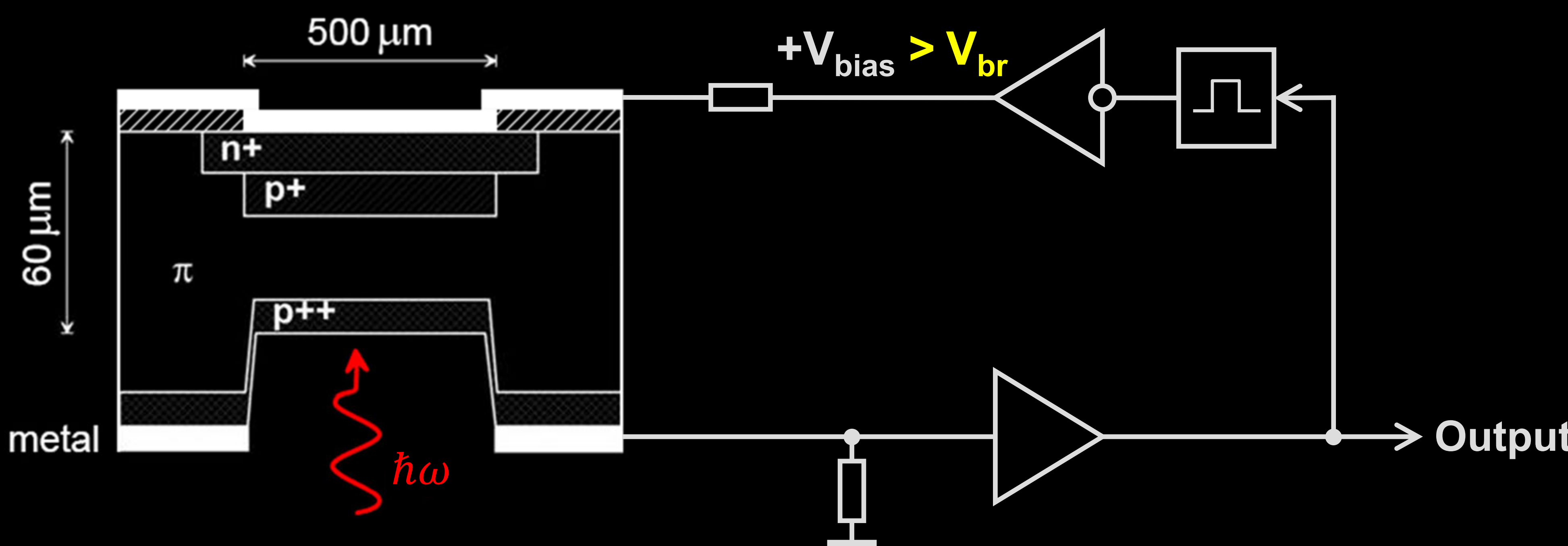


Image reprinted from: http://www.frankswebspace.org.uk/ScienceAndMaths/physics/physicsGCE/D1-5.htm

Single-photon avalanche photodiode



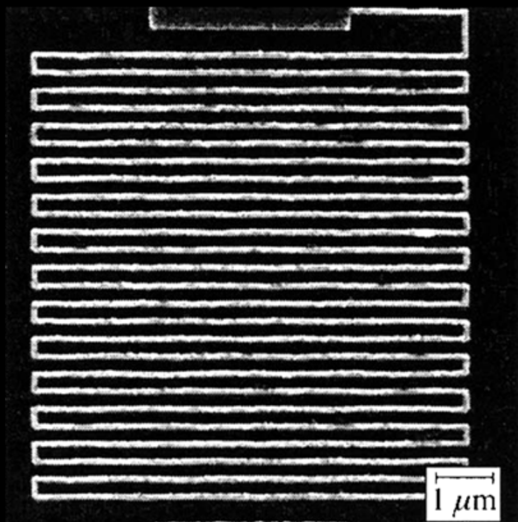


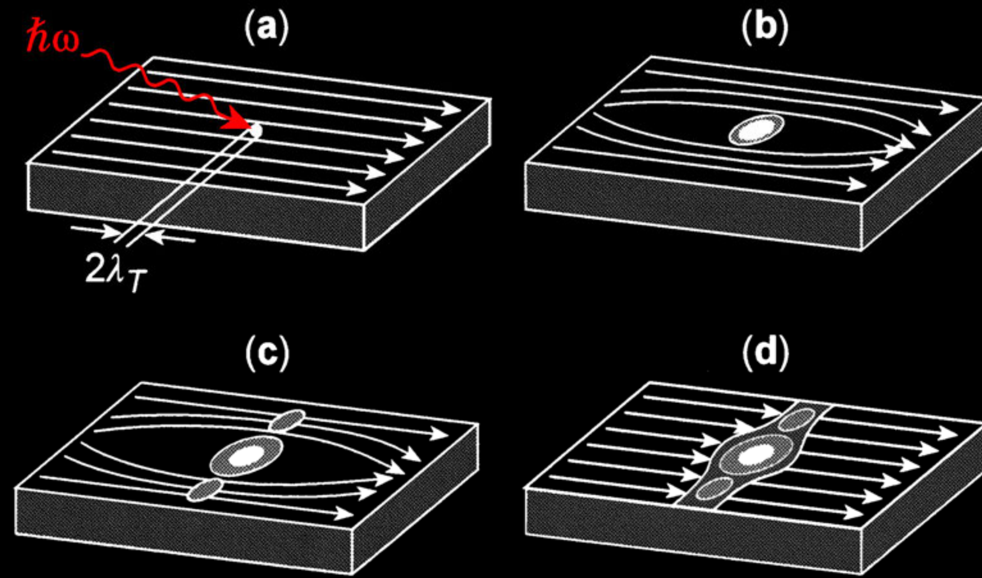


Images reprinted from: https://www.photonicsonline.com/doc/avalanche-photodiodes-theory-and-applications-0001; S. Cova *et al.*, J. Mod. Opt. **51**, 1267 (2004)

Superconducting single-photon detectors

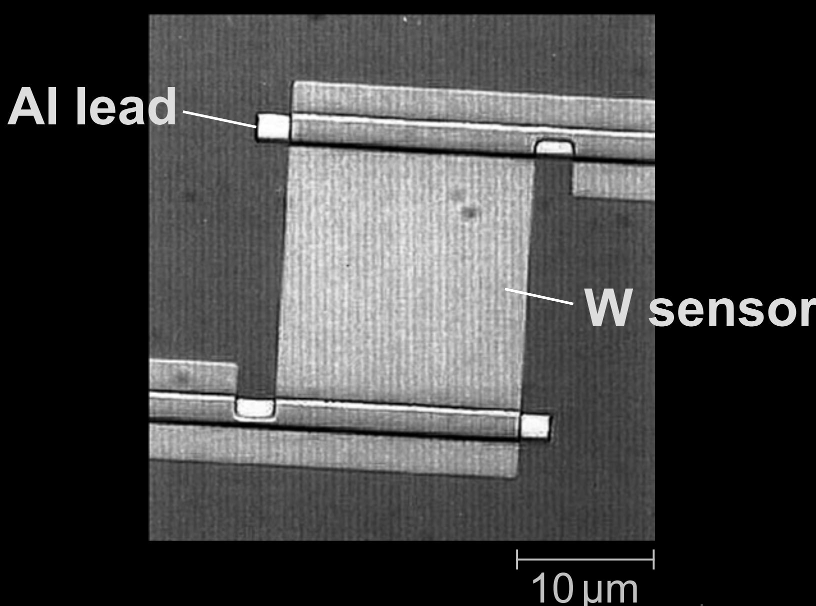
Superconducting nanowire

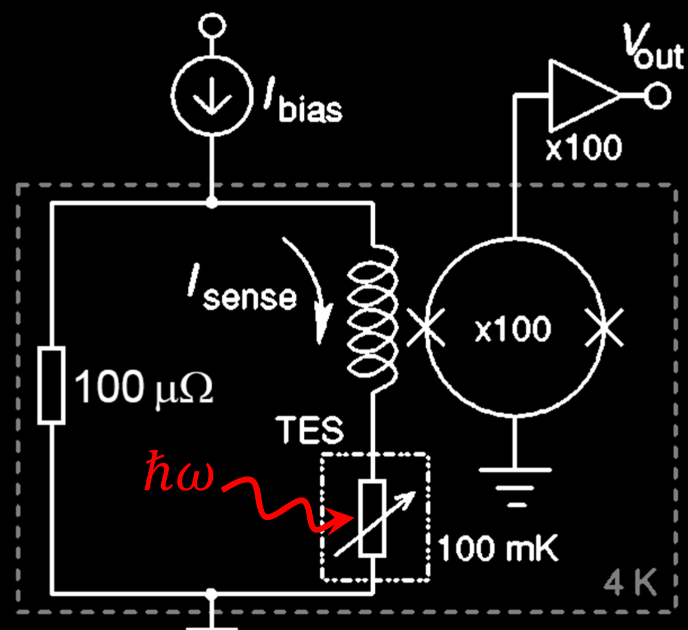




Images reprinted from: R. Sobolewski *et al.*, IEEE Trans. Appl. Supercond. **13**, 1151 (2003)

Transition-edge sensor



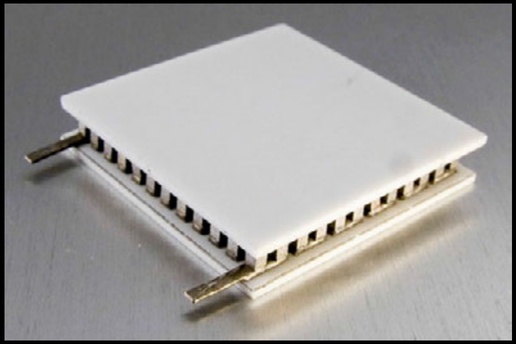


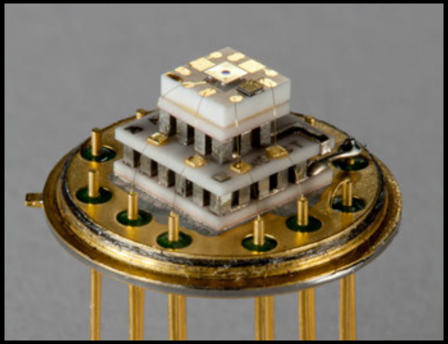
Images reprinted from: B. Cabrera *et al.*, Appl. Phys. Lett. **73**, 735 (1998); A.J. Miller *et al.*, Appl. Phys. Lett. **83**, 791 (2003)

Cooling requirements

Photomultiplier: room temperature

Avalanche photodiode: −50 °C





Thermoelectric cooling

0 5 mm

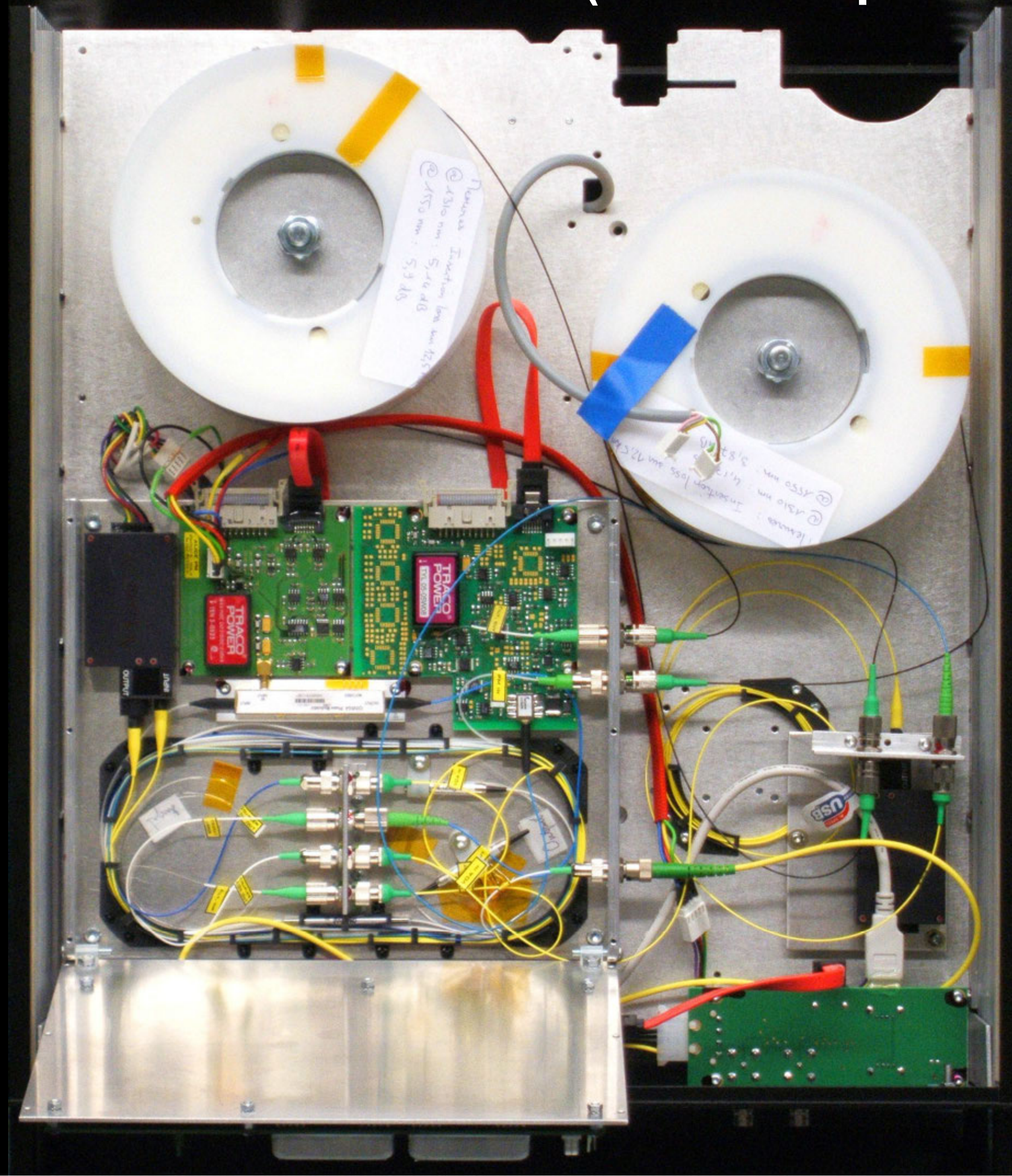
Superconducting nanowire: 4 K

Transition-edge sensor: 100 mK

Images reprinted from: Kryotherm; S. Sauge *et al.*, Opt. Express **19**, 23590 (2011); Advanced Research Systems; University of Cape Town

Assembled fiber optics

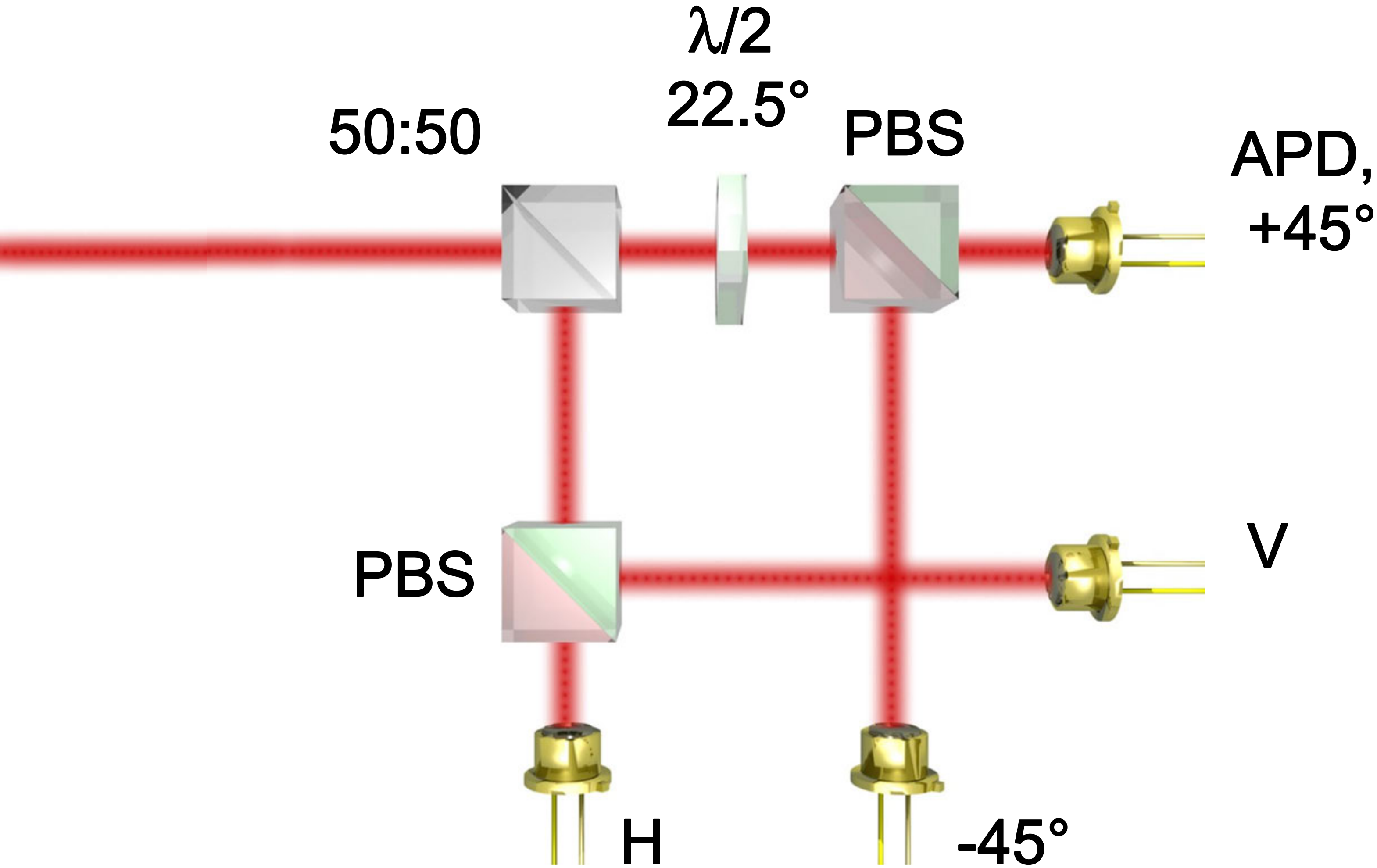
Quantum key distribution unit Alice (ID Quantique Clavis2)



0 100 mm

Assembled free-space optics

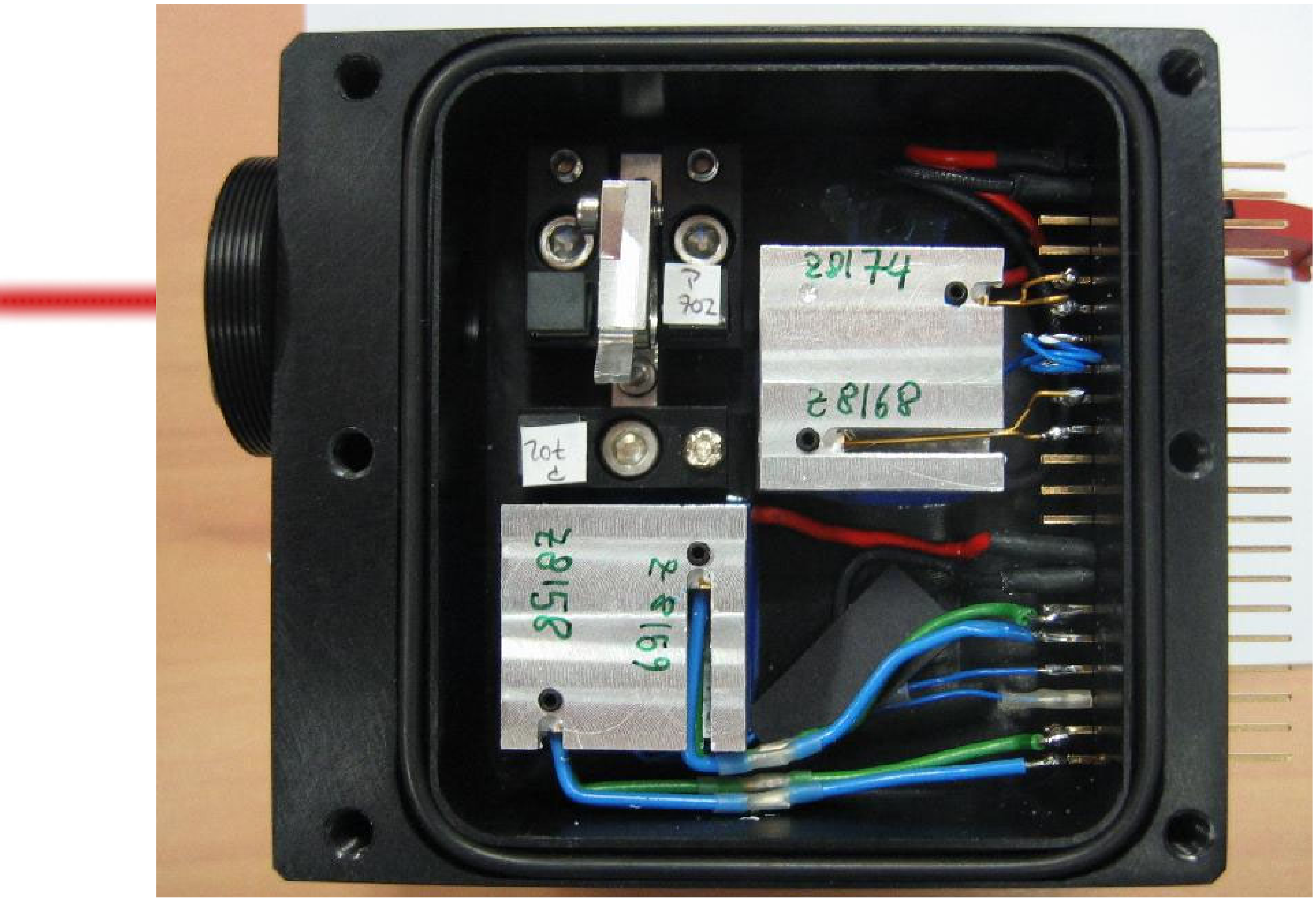
Bob's polarization analyzer with single-photon detectors



J. G. Rarity, P. C. M. Owens, P. R. Tapster, J. Mod. Opt. **41**, 2435 (1994)

Assembled free-space optics

Bob’s polarization analyzer with single-photon detectors

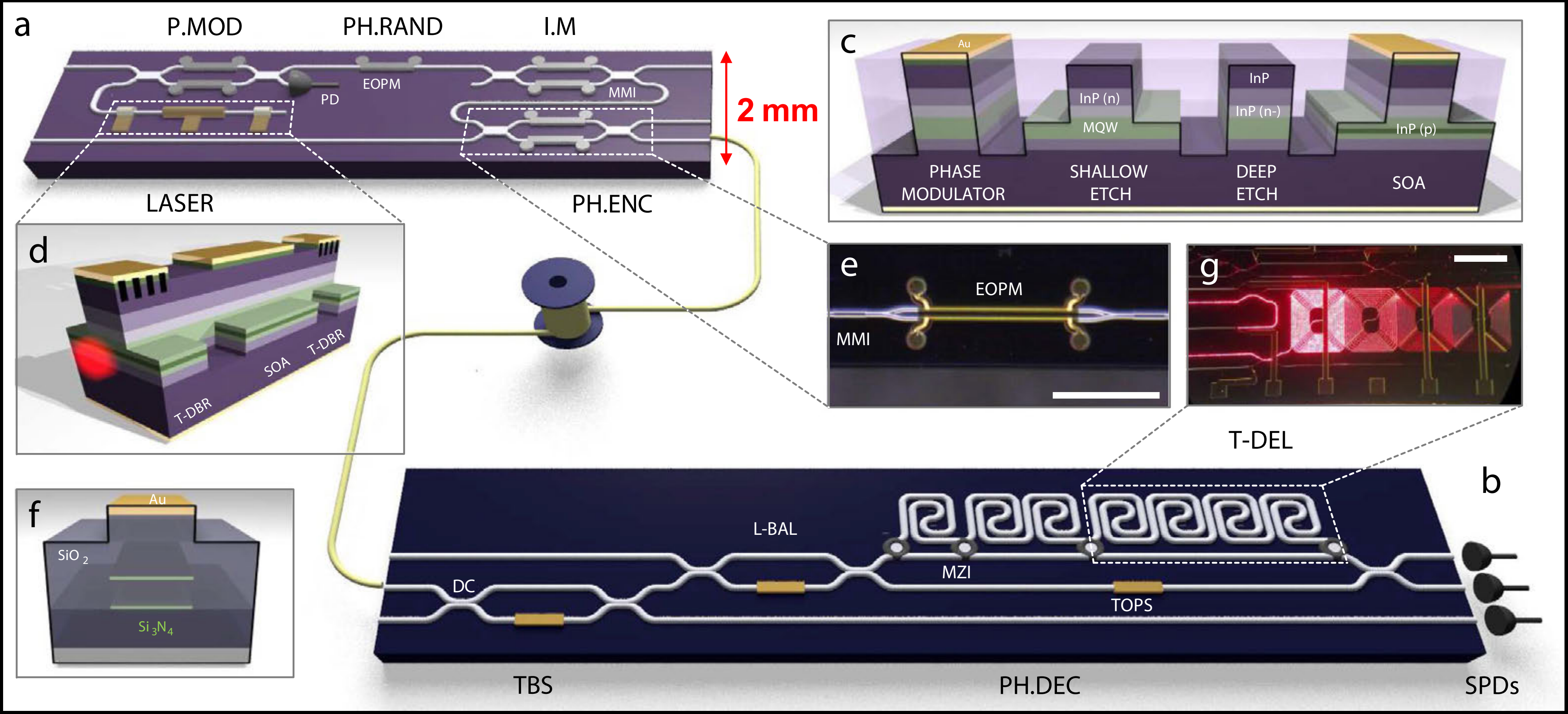


0 10 mm

J. G. Rarity, P. C. M. Owens, P. R. Tapster, J. Mod. Opt. **41**, 2435 (1994)

Emerging: integrated optics

Quantum key distribution system



P. Sibson *et al.*, Nat. Commun. **8**, 13984 (2017)
A. W. Elshaari *et al.*, Nat. Photonics **14**, 285 (2020)